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(DARPA) QUANTUM-LIMITED MEASUREMENT AS A TOOL FOR ENTANGLEMENT IN SUPERCONDUCTING CIRCUITS

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14. ABSTRACT

Under the QuEST program the McDermott developed a variant of the dc SQUID that is optimized for amplification of microwave frequency signals. Here the gain element is more properly termed a Superconducting Low-inductance Undulatory Galvanometer (SLUG) as the input signal is injected directly into the loop inductance as a current. The microwave SLUG amplifier has achieved system added noise less than one quantum at 6 GHz, and demonstrated improvement in single-shot cQED qubit measurement fidelity from 60% (with a low-noise HEMT alone) to 99% in 600 ns. The SLUG microwave amplifier is an extremely promising readout technology for scalable superconducting surface codes due to its simple dc biasing requirements, large instantaneous bandwidth, high saturation power, and intrinsic reciprocity.

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Under the QuEST program the McDermott developed a variant of the dc SQUID that is optimized for amplification of microwave frequency signals. Here the gain element is more properly termed a Superconducting Low-inductance Undulatory Galvanometer (SLUG) as the input signal is injected directly into the loop inductance as a current. The microwave SLUG amplifier has achieved system added noise less than one quantum at 6 GHz, and demonstrated improvement in single-shot cQED qubit measurement fidelity from 60% (with a low-noise HEMT alone) to 99% in 600 ns. The SLUG microwave amplifier is an extremely promising readout technology for scalable superconducting surface codes due to its simple dc biasing requirements, large instantaneous bandwidth, high saturation power, and intrinsic reciprocity. Our work on development of high-performance phase-insensitive linear amplifiers under the QuEST program was published as Mueck et al., Appl. Phys. Lett. 94, 132509 (2009), Ribeill et al., J. Appl. Phys. 110, 103901 (2011), and Hover et al., Appl. Phys. Lett. 100, 063503 (2012). The lead graduate student on these experiments, David Hover, will receive his Ph.D. in September 2013 and has accepted a postdoctoral position in the superconducting qubit group of MIT/Lincoln Labs.

In other work, the McDermott group has developed a microwave-frequency analog of the avalanche photodiode, the prototypical photon counter of familiar quantum optics protocols. The detector is a large-area Joesphson junction that is biased close to its critical current, such that absorption of a single microwave photon promotes the junction from the ground state to the first excited state. From the excited state the junction tunnels rapidly to the continuum, producing a large and easily measured classical voltage pulse. With a single junction circuit we achieve detection efficiencies of order 90%. With a two-junction counter circuit, we have performed a microwave-frequency coincidence counting version of the classic Hanbury Brown and Twiss experiment, demonstrating microwave photon bunching from a thermal source. This work was published as Chen et al., Phys. Rev. Lett. 107, 217401 (2011). In recent work, we have theoretically demonstrated the viability of high-fidelity readout of transmon qubits using microwave photon counting, and experiments are currently underway to demonstrate scalable qubit readout with counters. The lead postdoc on these experiments, Yung-Fu Chen, is now on the physics faculty at National Central University in Taiwan.

Finally, the McDermott group has developed improved phase qubit circuits and has probed the strong coherent interaction between the qubit and bosonic modes realized in lumped element resonators. A key piece of technology that enabled this work was the realization of high-Q qubit shunt capacitors from the crystalline silicon membrane of an SOI wafer. Recent developments include the realization of superconducting aluminum vias that connect the circuit grounds on the top and bottom faces of the crystalline silicon membrane; this fabrication development allows the realization of a more robust microwave design. We plan on writing a manuscript on the improved phase qubit work in the coming months. In ongoing work, the McDermott group is developing multiqubit transmon circuits to use as a testbed for the exploration of scalable measurement strategies in the superconducting surface code.

At Syracuse, throughout the QuEST project the Plourde group has made significant progress in developing ultra-low noise amplifiers based on variants of the dc Superconducting QUantum Interference Device (dc SQUID) for measuring the weak signals corresponding to entanglement between superconducting qubits and microwave photons. The Plourde group has focused on dc SQUIDs with a resonant microstrip input coil and sub-micron Al-AlOx-Al Josephson junctions patterned using precision electron-beam lithography at the Cornell NanoScale Facility. The small junction size has allowed for the use of significantly larger shunting resistances, which resulted in increased transfer functions, and hence higher gain, for the SQUIDs. The initial designs resulted in amplifiers operating at 1.55 GHz with 30 MHz of bandwidth and over 30 dB of gain [DeFeo et al., Appl. Phys. Lett. 97, 092507 (2010)]. In subsequent device designs, the Plourde group optimized the SQUID and input-coil layout, resulting in an amplifier with substantial gain near 4 GHz and 150 MHz of bandwidth. This amplifier was measured with a cryogenic HEMT post-amplifier and a novel noise-characterization procedure was applied to measure a minimum system noise temperature of 0.55 K, a significant improvement to the system noise without the SQUID amplifier present [DeFeo & Plourde, Appl. Phys. Lett. 101, 052603 (2012)]. The lead graduate student working on this SQUID amplifier development, Michael DeFeo, successfully defended his Ph.D. thesis on this topic at Syracuse in the summer of 2012. Since leaving Syracuse he has been a postdoctoral scientist at NIST Boulder working on new experiments probing entanglement in superconducting qubit systems.

During the QuEST project, the Plourde group has also worked on the development of lumped-element superconducting oscillators for the implementation of a quantum non-demolition measurement scheme for superconducting qubits. The oscillators were fabricated with a dc SQUID using sub-micron Al-AlOx-Al Josephson junctions with a large superconducting parallel-plate capacitor shunting the SQUID. Extensive measurements were performed by driving the SQUID oscillator with a narrow resonant microwave burst, as short as 1 ns, then observing the subsequent ringdown oscillations with low-noise amplification. The inherent nonlinearity caused by the Josephson junctions of the SQUID resulted in intriguing behavior, especially as the Josephson inductances were tuned by a magnetic flux or the excitation signal resulted in currents approaching the critical current of the junctions. Prior to this work, a detailed study of the response of a kicked nonlinear oscillator had not been performed. Throughout the project, the Plourde group has worked closely with the theoretical group of Frank Wilhelm to model the dynamics of the SQUID oscillators. Extensive numerical simulations have yielded quite good agreement with the experimentally measured ringdown oscillations for various flux biases and excitation amplitudes [Bhupathi et al., manuscript in preparation].

The Plourde group has also worked on a variety of circuit-QED systems to study cavity-qubit entanglement. Some experiments have probed the interactions between capacitively shunted flux qubits that were inductively coupled to a narrow constriction at the current antinode of a superconducting microwave resonator. This resulted in vacuum Rabi splittings in excess of 1 GHz, thus reaching the ultra-strong coupling regime. The Plourde group has also made extensive measurements of asymmetric transmon qubits coupled to

cavities, including the implementation of a novel frequency-modulation technique for driving first-order sideband transitions between the qubit and cavity.

The theoretical physics group of co-PI Frank Wilhelm-Mauch has operated out of the University of Waterloo, Canada in the first part and Saarland University, Germany, in the second part of this program.

Main pieces of work:

1. A key aspect of our work has been the theory of the Josephson Photomultiplier (JPM). We have fully analyzed its backaction and its measurement performance based on a simple three-level model. We have shown that ideal operation can be reached with the JPM with a short T_2 and a long T_1 as can be reached by implementing an RC-shunt. In this case, cohrent oscillations between cavity and detector disappear and the backaction operator ideally reflects the charactierstics of the detection scheme: It provides an ideal dichotomic detector in the sense tha it can detect the presence of absence of photons but has no number resolution beyond that. The corresponding backaction operator is the photon subtraction operator that lowers the photon number by one with, unlike the standard lowering operator, a constant, number-independent prefactor.

Quite to our surprise, but very naturally in hindsight, this backaction can be used to change the measured states to the point that it is possible to create nonclassical states out of classical ones. This is contrary to the typical situation in quantum measurement where the backaction turns nonclassical states into classical ones. The reason for this counterintuitive effect is that the observable being measured does not have any classical counterpart - its definition inevitably relies on the Planck quantum. We have developed a protocol that creates squeezed states, cat states, squeezed cats, Voodoo cats, and compass states based on classical microwave pulses as well as measurment. Other than most postselection-based protocols, both success probabilty and fidelity are high enough to be practical.

We have performed a simulation of a JPM exposed to a weak classical pulse and showed that it can detect radiation with remarkably large bandwidth up to 1 GHz, violationg typical linear response relations on gain-bandwidth products. This is connected to the strong nonlinearity of the JPM. It is a resonant tunneling phenomenon that is based on the slightly different level spacings in the metastable vs. the detection well. These lead to a series of resonant tunneling peaks which by adding some damping all merge into one.
In order to do this, we had to analyze the full JPM potential in the deep well case, and solve the master equatin for it.

2. We have performed detailed studies of ringdown oscillations in pulse-driven SQUIDs. These simulations were detailed two-dimensional Langevin simulations backed up by analytical arguments. The simulations have excellent agreement with experiments and are a contribution to the remarkably weakly explored theoretical field of pulse-driven multidimentional nonlinear oscillators. In the weak driving case, we can discriminate the resonant regime that has a long ring-down and the detuned regime, where the response

amplitude quasi-adiabatically follows the pulse shape. In the off-resonant case, we observe the interplay of dynamical detuning, phase randomization, and finite-range jumps between different local minima of the SQUID potential.

3. We have analyzed different protocols for state tomography using the tools developed in this project. One can directly show that the JPM measures the Husimi Q-funtion of the state. We have investigated a number of ideas for adaptive measurements and developed adaptive Bayesian strategies for qubits that need to be transferred into cavities.

4. We have worked with the McDermott group to analyze their HBT experiments.

5. As a non-anticipated surprise, our tool for studying the JPM bandwidth provides a macroscopic model of avoided level crossings in phase qubits and related superconducting structures. This model, which does not make any assumptions about imperfect materials, is in striking agreement with a range of experiments in superconducting qubits. The connection to QuEST was that for the bandwidth calculation we had to develop a tool that exactly diagonalizes the JPM potential, leading to all eigenstates and even very weak couplings in the deep well case.